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A *CHANDRA* SEARCH FOR X-RAY JETS IN REDSHIFT 6 QUASARS

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ABSTRACT

We have searched for X-ray jets in the recent *Chandra* observations of three Sloan Digital Sky Survey (SDSS) quasars at redshift z $\approx$ 6. All 3 quasars were detected in X-rays in these relatively short observations. SDSS1030+0524 is not consistent with a point source, and may be a gravitationally lensed system. We find a possible jet-like feature 23$''$ from the quasar SDSS 1306+0356. We can explain the emission by inverse Compton (IC) scattering off the Cosmic Microwave Background (CMB), assuming that the intrinsic properties of the system are similar to X-ray jets at z<1. Deeper observations to investigate the interpretation as a jet will be practical.

Subject headings: galaxies: quasars: general— galaxies: jets—galaxies: quasars: individual (SDSSp J083643.85+005453.3, SDSSp J103027.10+052455.0, SDSSp J130608.26+035626.3)— X-rays: galaxies

1. INTRODUCTION

The sub-arcsecond angular resolution of the *Chandra* X-ray Observatory has proven to have unique capability to resolve jets and hot-spots in quasars and radio sources. This was shown in the very first pointed observation (Schwartz et al. 2000; Chartas et al. 2000), at the z=0.652 quasar PKS 0637–752 for which Schwartz et al. (2000) showed that the X-rays could not plausibly arise from the synchrotron mechanism. To explain the X-ray emission, Tavecchio et al. (2000), and Celotti et al. (2001) suggested that bulk relativistic motion of the jet would allow the X-rays to be produced by inverse Compton (IC) radiation from the cosmic microwave background (CMB), while allowing the magnetic fields and relativistic electrons to be near equipartition in the jet rest frame. Schwartz (2001, 2002) noted that if observed X-rays were produced by IC/CMB, whether or not relativistically beamed, then such a source would be seen at any larger redshift with the same surface brightness, and would be resolved and detected by *Chandra*.

Fan et al. (2001) have discovered the three most distant quasars known, at redshifts 6.28, 5.99, and 5.82. A Director's Discretionary Program (cf. http://cxc.harvard.edu/DDT/DDTobs_info.html) proposed by Brandt was carried out on 29 January, 2002 to obtain "snapshot" data for immediate public use in planning further studies of distant quasars. We have used these data to search for X-ray jets associated with those quasars.

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2. OBSERVATIONS OF THREE SDSS QUASARS AT REDSHIFT 6

The observations were carried out in the standard 6-chip ACIS-S imaging mode, with a 3.2s frame time, and events telemetered in the 3×3 faint mode format. We have selected for analysis only the data from S3, with ASCA grades 0,2,3,4,6, and energy between 0.5 and 7 keV. At lower energy the quantum efficiency and energy response is increasingly uncertain, and at higher energies the background is increasing steeply.

Table 1 summarizes the observations. The observing time is taken from the number of frames, times the 3.2s frame time. For the core, we tabulate the measured counts in a $1''.23$ radius about the quasar position (5 pixel diameter), giving $\sim 95\%$ encircled energy fraction at 1.5 keV (Jerius, et al. 2000). We convert from a measured counting rate in the 0.5–7 keV band to an unabsorbed, measured flux in that band assuming a power law spectrum of energy index 0.7, and the galactic hydrogen column density. This is approximately 6.0×10^{-12} ergs cm^{-2} s^{-1} per count s^{-1}. The factor changes about $\pm$ 1.5% for the range of column densities of the three objects, 2.1 to 4.4 $\times10^{20}$cm^{-2}, and changes by about $\pm$ 20% for indices from 0.4 to 1.2. Poisson statistics on the few detected counts dominate the uncertainty. The final two columns convert to rest frame luminosity in the 2–10 keV band[2], including the K-correction for the assumed spectrum.

Figure 1 shows the detection of each quasar. The plus sign gives the true position of the quasar (Fan et al. 2001). The X-ray centroids are offset by $0''.65$, $0''.76$, and $0''.66$, respectively for SDSS 0836, SDSS 1030, and SDSS 1306. These are within the astrometric performance of *Chandra* (cf. http://cxc.harvard.edu/cal/ASPECT/celmon/). Each quasar is clearly detected. The background rates are determined from large rectangular regions to be 2.04, 2.56, and 2.92 $\times10^{-3}$ counts per pixel, respectively, so there is a negligible background correction of 0.04 to 0.05 counts, which we do not make. In the 19 pixel source extraction circles, the probability is less than 2.6×10^{-5} of getting 3 or more counts, so all the detections are highly significant. (For a serendipitous source anywhere in the field, one only needs 4 counts to have less than a 1% probability of a chance occurrence.) SDSS 0836 and SDSS 1306 are clearly consistent with being point sources.

The 6 photons from SDSS 1030+0524 are highly unlikely to be from a single point source. They are all further than $0''.68$ from their centroid. That distance is the 79% encircled energy radius, so the probability is 8.6×10^{-5} that all six photons would fall outside this radius. There is a 4.7% chance that one is due to background, but less than 0.13% chance that two or more are background counts. If we discard the most distant photon and recompute the X-ray centroid, one falls at the 55% encircled radius and the other four are still outside the 80% radius, and the probability of at least four so distant from the centroid is only 6.7×10^{-3}. Therefore either the source is extended, over about a $2''$ diameter, or it is really two or more point sources. As discussed by Wyithe & Loeb (2002a,b), there is a probability between 7% and 30% that any quasar at z=6 is gravitationally lensed, and this could be confirmed with a followup observation of >50 ks.

Figure 2 shows the region surrounding each quasar. For the cosmological parameters used here, $1''$ corresponds to 6.26, 6.00 and 6.16 kpc for SDSS 0836, SDSS 1030, and SDSS 1306, respectively. The larger circles indicate a 100 kpc projected distance from each quasar. There are no significant concentrations of photons anywhere within these circles. In the annulus we expect 6.8, 9.3, and 10.0 background counts and observe 6, 14, and 8, respectively.

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[2]We use $H_0 = 65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and a flat universe with $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, and q_0 = -0.55 throughout.

SDSS 1306+0356 has a significant X-ray feature 23.″3 to the NE of the quasar, at a distance 143 kpc projected in the plane of the sky. There are 7 counts in a box 5″×2″ which points toward the quasar. The significance of these as an X-ray source is beyond doubt. We can arbitrarily place this box to include at least one count. Since there are only 0.13 background counts expected, the chance of getting 6 additional counts in a 10 arcsec^2 box is only 5.8×10^{-9}, or only 1.7×10^{-4} of occurring in any 10 arcsec^2 box within 5′ of the quasar. There is no visible object at this position in the digital sky survey. The FIRST radio survey gives an upper limit of 0.93 mJy at 1.4 GHz at this position (White et al. 1997). Interpretation as an IC/CMB X-ray jet is entirely reasonable, as we discuss below; however, there is no specific evidence requiring such interpretation. Arguments as given above for the core of SDSS 1030 rule out a single point source, with or without attributing any of the 7 counts to background. The spatial distribution of counts cannot rule out two point sources and a background count. Giacconi et al. (2001) give about 200 sources deg^{-2} above the flux of 5×10^{-15} observed from the jet, so there is a 5% chance of one such source falling within 1′ of the quasar. The chance occurrence of an extended source at this flux level is at least 10 times smaller, <0.5% (see Bauer et al. (2002)). Because a longer X-ray observation is needed to obtain definitive information, and because we cannot rule out the possibility of foreground sources correlated with each other, we do not attempt a more exhaustive discussion of the probabilities. As a newly discovered X-ray source, we designate this as CXOU 130609.31+035643.5.

In Table 1 we set a limit to the flux of putative jets in SDSS 0836 or SDSS 1030 by noting that we do not find 3 or more photons in any similar 10 arcsec^2 box pointing toward the core. If there were a jet from which we expected 6.3 or more counts, then there would be less than a 5% probability to fail to detect 3 or more, and we adopt this as our limit.

Because of the small numbers of photons, we need to give careful consideration to systematic effects. Figure 3 shows that the background was steady during these observations, and the arrival times of the quasar and jet counts are consistent with being uniform throughout the observations. No two counts were registered from the same physical pixel.

To investigate any peculiarities in the distribution of photon energies, we perform a KS test of the energy distributions of the photons from each quasar and from the jet feature against the core spectrum of 3C 273. We might expect them *a priori* to have a non-thermal spectrum of energy index roughly $\alpha \sim 0.7$. Figure 4 shows the cumulative distributions. The solid heavy line is the core spectrum of 3C 273, determined from 3063 photons in the readout streak in OBSID 1712 (Marshall et al. 2001). If SDSS 0836, SDSS 1030, SDSS 1306, and the jet all had the same spectrum as 3C 273, we would expect deviations as large as actually observed 98%, 16%, 96%, and 10% of the time, respectively. Thus we cannot reject this hypothesis for any of them. The crosses plot the distribution of 763 background photons from a source free region of the SDSS 1306 observation. Such large deviations as observed would be expected only 0.3%, 5.6%, 2.8%, and 90% of the time, for the same respective sources. Thus the quasar core spectra are very distinct from that of the background, while the putative jet spectrum is consistent with the harder background spectral shape.

We compute $\alpha_{\rm ox}$ according to the original definition (Tananbaum et al. 1979),

$$\alpha_{\rm ox} = -\log(f_x/f_o)/\log(\nu_x/\nu_o), \tag{1}$$

where f_x is the X-ray flux density at 2 keV, $\nu_x = 4.8\times10^{17}$ Hz, and f_o is the optical flux density at 2500 Å, $\nu_o = 1.2\times10^{15}$ Hz. The flux densities are computed in the rest frame. We take the AB_{1450} magnitudes from Fan et al. (2001) and extrapolate from 1450Å to 2500Å assuming a power law flux $\nu^{-0.5}$ (Richstone & Schmidt 1980; Vanden Berk et al. 2001). We find $\alpha_{\rm ox}$ of 1.66, 1.79, and 1.65, respectively, for SDSS

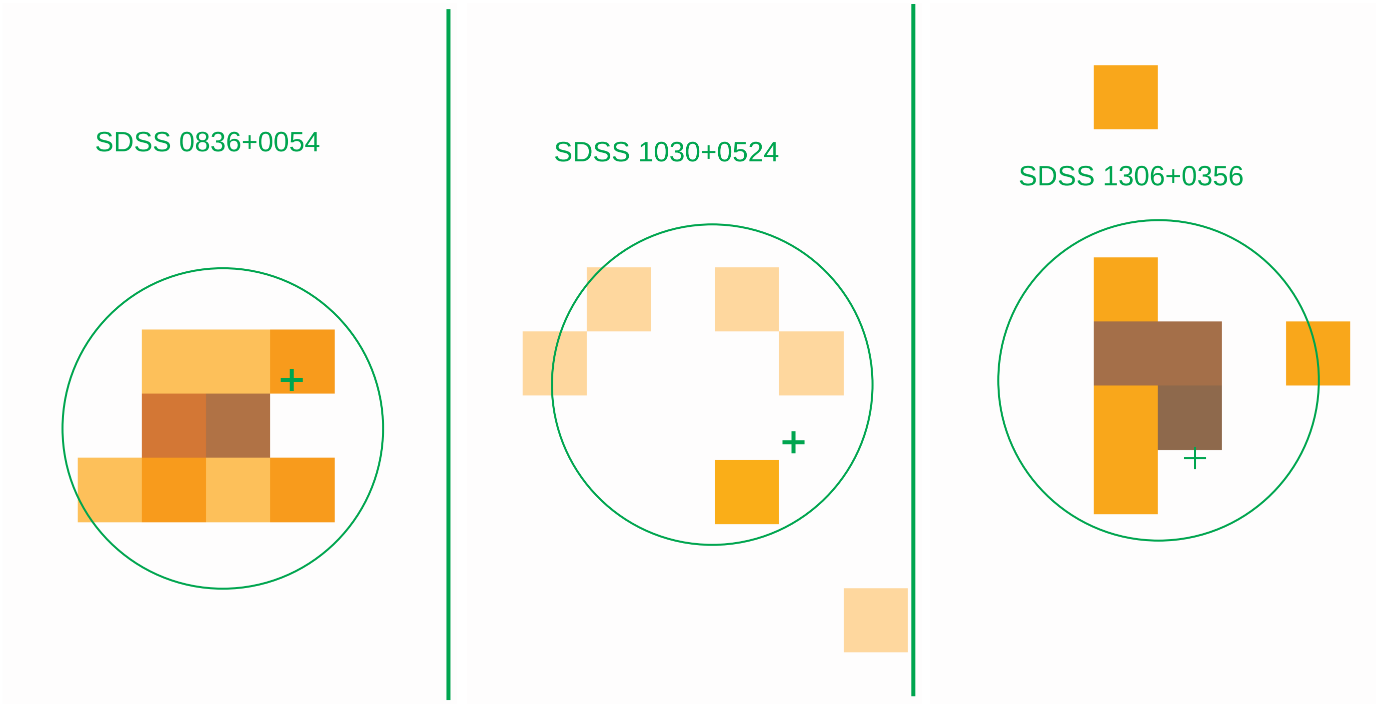

Fig. 1.— Detection of X-ray emission from the three SDSS quasars at z≈6. The plus signs show the positions given by Fan et al. (2001). The X-ray centroids are all consistent within the absolute astrometric accuracy of *Chandra*. In the 1.″23 radius extraction circles we find 21, 6, and 14 counts respectively, for SDSS 0836, SDSS 1030, and SDSS 1306. The pixels displayed have from 1 to 6 counts. The fields shown are 3.″5 × 5.″4. The X-rays are binned into 0.″4913 ACIS pixels.

0836, SDSS 1030, and SDSS 1306. These values are consistent with the range found by Vignali et al. (2001) for *Chandra* quasars at z>4, but about 0.1 larger numerically than the mean found by Kaspi, Brandt, & Schneider (2000) for *ROSAT* z>4 quasars. We note that an extraction circle larger than 25″ applied to SDSS 1306+0356 would lead to a decrease in $\alpha_{\rm ox}$ by 0.06, due to inclusion of flux from CXOU 130609.31+035643.5.

3. CAN CXOU 130609.31 BE AN X-RAY JET FROM SDSS 130608.26?

The feature discovered by *Chandra* to the NE of SDSS 1306 can be explained as a jet emitting by inverse Compton scattering on the CMB. No specific evidence prohibits a synchrotron mechanism, but such emission would imply much more severe energetic and lifetime constraints, while the IC/CMB process implies that the source will appear to have the same surface brightness at any redshift (Schwartz 2002). The ratio of synchrotron (radio) emission to IC (X-ray) emission from a population of electrons (Jones 1965; Felten & Morrison 1966) is

$$\frac{L_R}{L_X} = \frac{\mathrm{H}^2/(8\pi)}{\rho_{CMB}}. \tag{2}$$

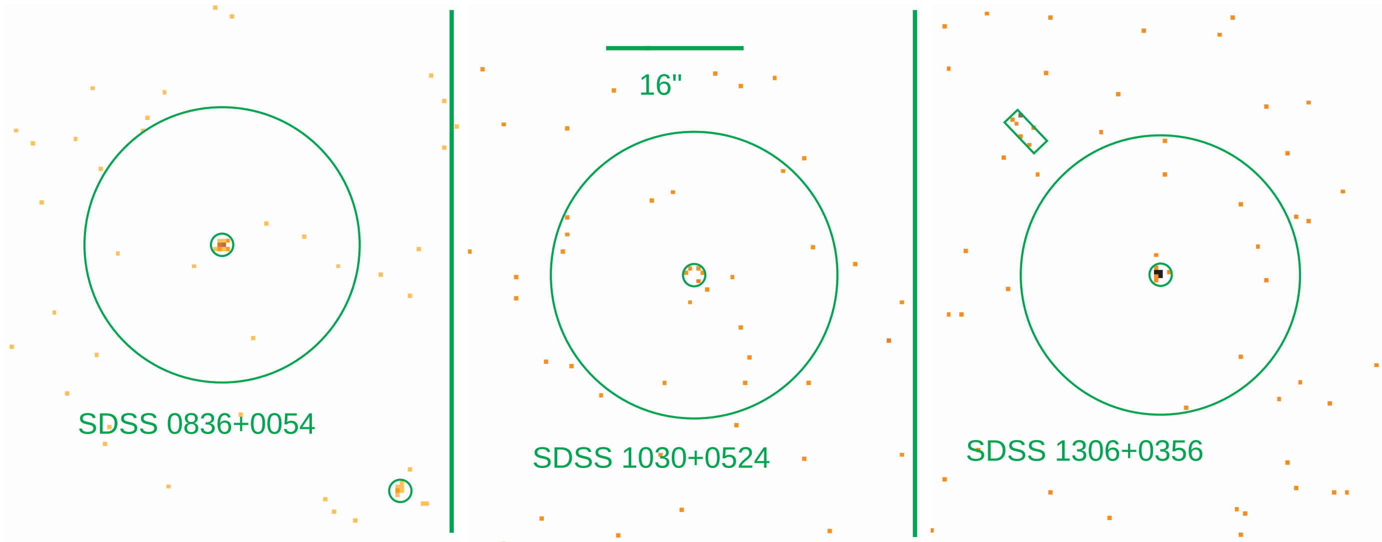

Fig. 2.— Fields of $52'' \times 62''$ around the SDSS quasars. The larger circles show a radius of 100 kpc, projected on the plane of the sky, at the distance of each quasar. These are $16''$ to $16''.6$. The box to the NE of SDSS 1306 has the $2''$ full width of the telescope response, and points toward the quasar core. It contains 7 counts where 0.13 are expected due to background. We interpret this as a possible jet, but cannot exclude other combinations of sources and background. The 7 photons to the SW of SDSS 0836 clearly show the condensation expected for a point source.

Since the energy density of microwave photons at the quasar is $\rho_{CMB} = \mathrm{aT}^4 = 7.56 \times 10^{-15}\ \mathrm{T}_0^4\,(\,1 + z\,)^4$ $= 10^{-9}$ergs cm^{-3} for the microwave temperature of $\mathrm{T}_0 = 2.728$ K (Fixsen et al. 1996) and redshift z=5.99, ρ_{CMB} will dominate any magnetic field of strength less than 160μG. But from the radio flux upper limit, we can derive a rest frame 100 MHz to 100 GHz radio luminosity of less than 3×10^{44} ergs s^{-1}, compared to the rest frame 3.5–49 keV X-ray luminosity of 1.3×10^{45} ergs s^{-1}, and deduce that H$\lesssim$80μG from equation 2.

Electrons with $\gamma \approx 1000$ will broadly scatter the CMB photons to observed energies around 1 keV. Their lifetime will be $2.1 \times 10^{12} / (\gamma\ (1{+}\mathrm{z})^4)$ years. Taking the volume corresponding to a cylinder $5''$ long and $1''$ diameter at the source distance, 1.1×10^{68}cm^3, gives a required energy density of 3.2×10^{-10} ergs cm^{-3} in relativistic electrons emitting the X-rays. A 90 μG field would be in equipartition with such an electron density. The magnetic field could be a factor of a few smaller, due to uncertainties in the quantities or the modeling assumptions, and since there is not yet a measured radio flux.

We would typically expect fields of only tens of μG based on observations of X-ray jets to date (Harris & Krawczynski 2002; Sambruna et al. 2002). Those observations have often required that the jet be moving with a bulk Lorentz factor Γ of at least a few, (see Harris & Krawczynski (2002); Sambruna et al. (2002)), in order that the CMB energy density be enhanced in the rest frame of the jet by a factor Γ^2, and still preserve equipartition of the magnetic field and relativistic particle energy densities. Because of the large redshift we need not invoke relativistic beaming to explain the present observations. However, it is certainly allowed, as long as the jet is pointed within an angle $\arccos(\sqrt{(\frac{\Gamma-1}{\Gamma+1})})$ of our line of sight, so that the apparent flux is not diminished.

That the jet flux is about 40% of the quasar core flux in this case is consistent with the ratios of

roughly 1% commonly observed in X-ray jets[3] if we assume that the jet magnetic field is approximately 30 μG. In that case, if this object were at a redshift z=2, the core flux would be enhanced a factor of 14. The jet surface brightness would remain the same due to compensating factors of $(1+z)^4$ in the microwave energy density and the cosmological dimming, and the solid angle would be about a factor of 2 smaller, for a net decrease in the jet to core ratio to about 1.5%. At redshifts less than 2, if it were not relativistically beamed, the CMB energy density would be less than the magnetic field energy density and the intrinsic X-ray emissivity of the jet would no longer be affected by the CMB.

Although the putative jet is about 30 kpc long, projected on the sky, there is an apparent gap of 130 kpc from the core to the jet, where the surface brightness is a factor of at least two smaller. This could be explained if the energy flux in this portion of the jet is primarily in the form of protons or Poynting flux, (cf. Harris & Krawczynski (2002)), or if it is mildly relativistic but away from our line of sight. In the latter case, the portion we see could be isotropic radiation after the jet becomes sub-relativistic.

4. CONCLUSIONS

All three z≈6 quasars were detected in relatively short *Chandra* observations. Their X-ray to optical luminosity ratios are median values for high redshift, high luminosity quasars, indicating that quasars at higher L_x/L_O, which are known to exist, will be detectable at if they exist at larger redshifts. Followup observations of all will be important to obtain rough spectral information, to investigate if SDSS 1030+0524 is gravitationally lensed, and to look more deeply for X-ray jets. In particular, the candidate jet from SDSS 1306 could be confirmed, or contradicted, by the spatial structure of 100 photons which would obtain in a 100 Ks observation. Radio emission should be detectable at $\gtrsim 100\mu$Jy at 5 GHz, by scaling from PKS 0637–752. This could be detected in a few hour VLA BnA observation. If confirmed, this will clearly indicate the possibility of detecting *only* the jet, and not core, X-ray emission from similar quasars at even larger redshifts.

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Table 1. Observations of the SDSS quasars at redshift 6

Name[a]	redshift[a]	Time(Ks)	Core Counts	Core Flux[b]	Jet Counts[c]	Jet Flux[b,c]	L_{core}[d]	L_{jet}[c,d]
SDSSp J083643.85+005453.3	5.82	5.686	21	2.2	< 6.3	<0.66	2.3	<0.70
SDSSp J103027.10+052455.0	6.28	7.942	6	0.45	<6.3	<0.48	0.55	<0.59
SDSSp J130608.26+035626.3	5.99	8.160	16	1.2	7	0.51	1.3	0.57

[a]Fan et al. (2001)

[b]Received 0.5–7 keV flux, unabsorbed, in units of 10^{-14}ergs cm^{-2} s^{-1}

[c]Detection is significant, but identification as a jet is not certain

[d]Rest frame 2 –10 keV luminosity in units of 10^{45}ergs s^{-1}

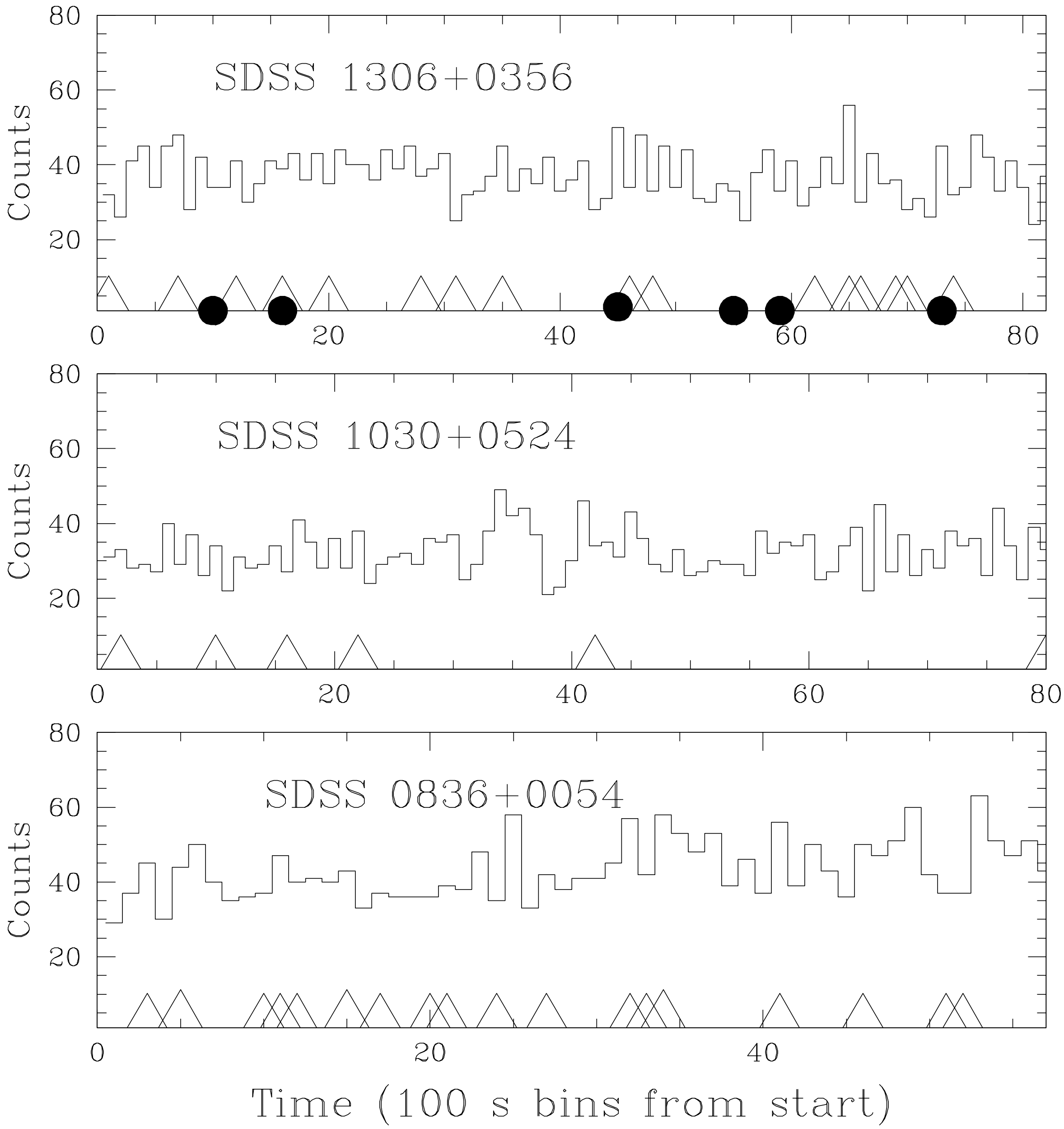

Fig. 3.— The solid histogram gives the arrival times of all 0.5 to 7 keV counts in the field, binned in 100s intervals from the start of each observation. (The final partial bin is not shown.) The upward triangles show the arrival time of each photon from the quasar extraction circle. The solid dots for SDSS 1306 show the arrival times of photons in the box which is a candidate as an X-ray jet.

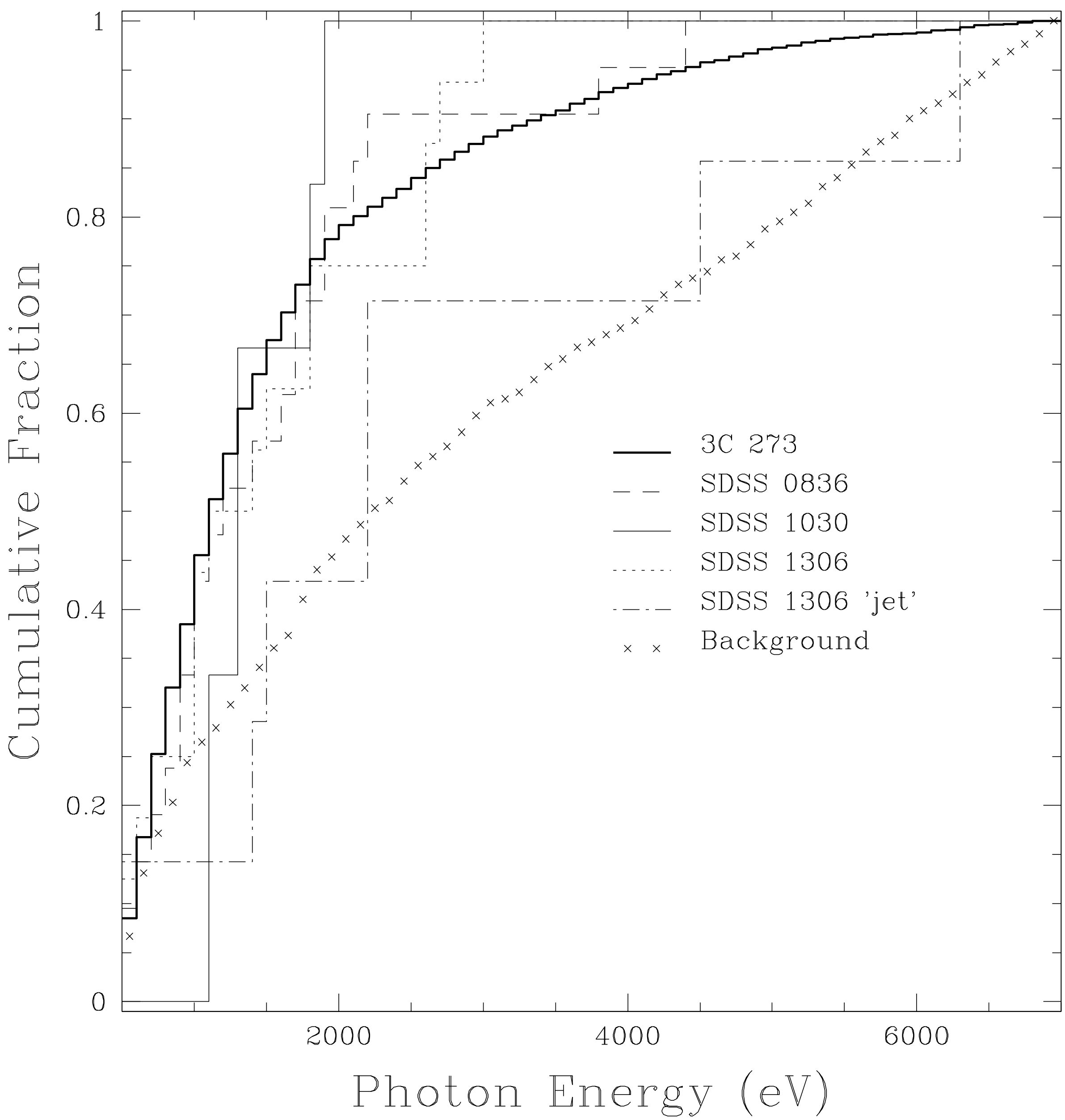

Fig. 4.— Integral probability distributions of the photon energies from the SDSS redshift 6 quasars. All photons are binned by 100 eV, from 500 to 7000 eV. A KS test allows all spectra to be consistent with the α=0.65 index of 3C273, shown as the heavy curve and based on 3063 photons. The jet spectrum is quite consistent with that of the background counts, shown as the small crosses, while the quasar spectra have only a small probability of consistency with the background spectrum.